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Arterial Blood Gases

E. P. TRULOCK, III

Definition

Arterial blood gases (ABGs) is a collective term applied to three separate measurements—pH, PCO_2 , and PO_2 —generally made together to evaluate acid–base status, ventilation, and arterial oxygenation. Oxygen (O_2) and carbon dioxide (CO_2) are the most important respiratory gases, and their partial pressures in arterial blood reflect the overall adequacy of gas exchange. PaO_2 is affected by age and altitude, Paco_2 by altitude. Therefore, PaO_2 must be individually calculated for each patient, and both determinations must be interpreted against local normal values. Hydrogen is not present in blood as a gas and, therefore, does not exert a partial pressure. However, pH, which measures hydrogen ion activity, is a conventional part of every arterial blood gas determination. The normal range for blood pH is 7.35 to 7.45.

Some calculated or derived variables may be reported with the ABGs. The bicarbonate concentration, which can be calculated from the pH and PCO_2 , is the most useful of these. Others, such as base excess and base deficit, are not essential and may be confusing.

Technique

Accurate results for ABGs depend on collecting, handling, and analyzing the specimen properly. Clinically important errors may occur at any of these steps, but ABG measurements are particularly vulnerable to preanalytic errors. The most common problems include nonarterial samples, air bubbles in the sample, either inadequate or excessive anticoagulant in the sample, and delayed analysis of an uncooled sample.

A proper blood sample for ABG analysis consists of a 2 to 3 ml arterial specimen collected anaerobically from a peripheral artery in a 3- or 5-ml plastic or glass, airtight syringe fitted with a small-bore needle. Any air bubbles inadvertently introduced during sampling must be promptly evacuated. Room air has a PO_2 of approximately 150 mm Hg (sea level) and a PCO_2 of essentially zero. Thus, air bubbles that mix and equilibrate with arterial blood will shift the PaO_2 toward 150 mm Hg and will lower the Paco_2 .

Heparin must be added to the syringe as an anticoagulant. Because the pH of heparin is near 7.0, and the PO_2 and PCO_2 of the heparin solution are near room air values, excess heparin can alter all three ABG measurements. Very little heparin is actually needed in the sample to prevent clotting; 0.05 to 0.10 ml of a dilute solution (1000 units/ml) will anticoagulate 1 ml of blood without affecting its pH, PCO_2 , or PO_2 . After flushing the syringe with heparin, a sufficient amount usually remains in the dead space of the syringe and needle for anticoagulation without distortion of the ABG determination.

After collection, the specimen should be analyzed expeditiously. If a delay of more than 10 minutes is anticipated,

the specimen must be immersed in an ice bath. Leukocytes and platelets continue to consume oxygen in the sample after it is drawn and can cause a significant fall in PaO_2 over time at room temperature, especially in the setting of leukocytosis or thrombocytosis. Cooling will prevent any clinically important effect for at least 1 hour by decreasing the metabolic activity of these cells.

ABGs are now routinely measured with an automated analyzer. The basic components of such a unit are three electrodes, one each for determining pH, PCO_2 , and PO_2 . The pH electrode measures the potential difference between a measuring electrode (which contains the sample in contact with a special glass membrane permeable only to H^+ ions) and a reference electrode (which has a known, stable pH). From the voltage across these electrodes, the sample pH is calculated. The PCO_2 electrode (Severinghaus electrode) employs an adaptation of the pH measurement. Carbon dioxide from the blood sample equilibrates across a gas-permeable membrane with a bicarbonate solution in a reaction that generates H^+ ions. The PCO_2 of the sample is determined indirectly by sensing the pH change in this solution. The PO_2 electrode (Clark electrode) determines PO_2 amperometrically. Oxygen from the blood sample diffuses across a semipermeable membrane and is reduced at the cathode of a polarographic electrode. This reaction produces a measurable current that is directly proportional to the sample PO_2 .

Each electrode is calibrated at two reference points in the typical operational range. For the pH electrode, two buffer solutions (pH = 6.840 and 7.384) are the standards. For the PCO_2 and PO_2 electrodes, two reference gases (usually 5% CO_2 , 20% O_2 , 75% N_2 ; and 10% CO_2 , 90% N_2) are utilized. After calibration, the accuracy and reliability of measurements may be checked by analyzing commercially available quality-control samples with known values of pH, PCO_2 , and PO_2 that span the range of common clinical values. Although these procedures generally ensure valid measurements, high PaO_2 values (>150 mm Hg) present a potential source of error. The PO_2 electrode is not linear and therefore may be inaccurate at values far beyond its calibration points (0 mm Hg and 140 mm Hg at sea level for the reference gases above). Consequently, the precision of PaO_2 values exceeding 150 mm Hg is uncertain unless the electrode has been recalibrated in an appropriate range, and this is not generally feasible in an automated analyzer.

The electrodes are maintained at 37°C in a thermostatically regulated waterbath; therefore, all ABG measurements are made at 37°C regardless of the patient's temperature. Nonetheless, pH, Paco_2 , and PaO_2 are all temperature dependent because gas solubilities are a function of temperature. When body temperature is higher than 37°C, the reported PaO_2 and Paco_2 measured at 37°C will be lower than the actual values in the patient; the converse holds when body temperature is below 37°C. Both equations and nomograms have been developed to adjust the 37°C

values to those corresponding to the patient's temperature. The equations, however, are too complex for easy calculation. The effect of varying temperature on a "normal" set of ABGs is illustrated in Table 49.1. Whether to correct ABG measurements (especially the PaO_2) to the patient's temperature or simply to report them at 37°C is a controversial issue, and laboratory practices vary in this area. It is relatively standard practice to report the pH and PaCO_2 at 37°C without correction. There is no uniform practice regarding PaO_2 , and the clinician must be familiar with local policy. As shown in Table 49.1, the effect of temperature changes on pH, PaCO_2 , and PaO_2 over the usual clinical range of 35° to 39°C is relatively small. The issue is clinically relevant primarily in hypothermia and hyperthermia.

Basic Science

The hydrogen ion (H^+) concentration determines the acid-base status of the blood. For convenience, the H^+ concentration is customarily expressed as pH, defined as the negative logarithm (base 10) of the H^+ concentration:

$$\text{pH} = -\log_{10} [\text{H}^+]. \quad (49.1)$$

Note that H^+ concentration and pH are inversely related; an increasing H^+ concentration (increasing acidity) corresponds to a declining pH, and vice versa. The normal H^+ concentration of 0.0004 mEq/L is equivalent to a pH of 7.40. The normal range of blood pH is 7.35 to 7.45.

The PaO_2 is the partial pressure of oxygen in arterial blood. The normal range for PaO_2 is affected by age and altitude. As a result of changes in overall matching of ventilation with perfusion, normal PaO_2 declines with advancing age. Regression equations have been published to estimate this decrease; however, there is some disparity in the results, probably attributable to heterogeneous study populations and nonuniform study conditions. Hence, these equations are only guidelines. For example, Sorbini et al. (1968) found the following prediction equation for supine subjects at sea level:

$$\begin{aligned} \text{PaO}_2 \text{ (mm Hg)} &= 109 - (0.43) (\text{age in years}) \\ \text{SD} &= \pm 4.10 \text{ mm Hg} \end{aligned} \quad (49.2)$$

Based on this equation, the lower limit of normal for PaO_2 at age 70 would be approximately 70 mm Hg.

At elevations above sea level, the partial pressure of inspired oxygen falls with the barometric pressure, and the normal PaO_2 decreases concomitantly. For example, at 1500 m (barometric pressure 634 mm Hg), the predicted normal PaO_2 in a healthy, young subject is approximately 80 mm

Hg; this contrasts with a value close to 95 mm Hg at sea level. Therefore, at locations substantially above sea level, local normal values that correct for altitude must be utilized in ABG interpretation.

The PaCO_2 is the partial pressure of carbon dioxide in arterial blood. The normal range is 35 to 45 mm Hg and does not vary significantly with age. Nevertheless, normal PaCO_2 tends to be lower at high altitudes because ventilation is stimulated, and local norms must be established.

Cellular metabolism and whole organ function are optimum over a relatively narrow range of pH. Hence, the acid-base status of the blood is closely regulated. Homeostasis is maintained by three mechanisms: (1) buffers that mitigate changes in pH, especially the carbonic acid/bicarbonate ($\text{H}_2\text{CO}_3/\text{HCO}_3^-$) pair; (2) the lungs, which control PaCO_2 ; and (3) the kidneys, which regulate plasma bicarbonate. The central relationship among these is the following reaction:



Dissolved CO_2 is hydrated in an equilibrium reaction to form the strong acid, H_2CO_3 . The amount of dissolved CO_2 is directly proportional to the PaCO_2 , the proportionality constant (α) being the solubility coefficient of CO_2 . Therefore, the lungs effectively regulate the H_2CO_3 concentration. Carbonic acid reversibly dissociates into H^+ and HCO_3^- . Metabolic acids are titrated primarily by HCO_3^- , and the HCO_3^- concentration is ultimately under renal control.

The interdependence among these may be expressed as the classic Henderson-Hasselbalch equation for pH or rearranged into an equation for $[\text{H}^+]$.

$$\text{pH} = \text{pK}' + \log ([\text{HCO}_3^-]/\alpha\text{PaCO}_2) \quad (49.3)$$

$$[\text{H}^+] = 24 (\text{PaCO}_2/[\text{HCO}_3^-]) \quad (49.4)$$

Notice in both equations that pH, or H^+ concentration, depends on the ratio of PaCO_2 to HCO_3^- , and not on the absolute value of either one alone.

Acidosis and alkalosis refer to pathophysiologic disturbances that tend to increase or decrease hydrogen ion concentration respectively. Primary disturbances in PaCO_2 cause the respiratory acid-base disorders, whereas primary alterations in bicarbonate are responsible for the metabolic derangements. Each primary disturbance elicits a compensatory response, which is usually incomplete, but returns the pH toward normal. Thus, an acidosis or alkalosis does not necessarily result in an acidemia ($\text{pH} < 7.35$) or alkalemia ($\text{pH} > 7.45$). The simple acid-base disorders are illustrated in Table 49.2. Mixed acid-base disturbances are

Table 49.1
Temperature-Corrected Values for a "Normal" ABG

Temperature (°C)	pH	PaCO_2 (mm Hg)	PaO_2 (mm Hg)
20	7.65	19	27
30	7.50	30	51
35	7.43	37	70
37	7.40	40	80
39	7.37	44	91

Source: Adapted and reproduced with permission from Shapiro BA, Harrison RA, Walton JR. Clinical application of blood gases. 3rd ed. Copyright © 1982 by Year Book Medical Publishers, Inc., Chicago.

Table 49.2
Simple Acid-Base Disorders

Disorder	Primary disturbance	Compensatory mechanism
<i>Respiratory</i>		<i>Renal</i>
Acidosis	↑ PaCO_2	H^+ excretion; HCO_3^- generation/retention
Alkalosis	↓ PaCO_2	HCO_3^- excretion
<i>Metabolic</i>		<i>Ventilatory</i>
Acidosis	↓ HCO_3^-	Hyperventilation (↓ PaCO_2)
Alkalosis	↑ HCO_3^-	Hypoventilation (↑ PaCO_2)

the result of two or more simple disorders occurring together. While these are more complex, their recognition and analysis are predicated on a thorough understanding of the primary disorders.

The primary purposes of respiration are to provide oxygen to the cells for aerobic metabolism and to excrete the carbon dioxide produced by this metabolic activity. This requires the integrated function of both the respiratory system for gas exchange between alveolar air and pulmonary capillary blood, and the cardiovascular system for gas transport to and from the metabolizing tissues. The respiratory system may be divided into two parts: the respiratory pump and the lung. The respiratory pump includes the thoracic cage and abdomen, the respiratory muscles, the respiratory control centers, and the neural interconnections. The major function of the respiratory pump is ventilation of the lung, whereas the primary role of the lung itself is gas transfer. Factors that influence gas exchange in the lung include (1) movement of gas into and out of the lung (ventilation); (2) blood flow through the lung (perfusion); (3) the regional distributions of ventilation and perfusion (ventilation-perfusion matching); and (4) diffusion across the alveolar-capillary membrane. The overall adequacy of gas exchange for oxygen and carbon dioxide is reflected by the P_{aO_2} and P_{aCO_2} .

Carbon dioxide, the major by-product of oxidative metabolism, is transported to the lung in venous blood and eliminated through alveolar ventilation. The P_{aCO_2} is directly proportional to carbon dioxide excretion rate (\dot{V}_{CO_2}) and inversely proportional to alveolar ventilation (\dot{V}_A).

$$P_{aCO_2} = K (\dot{V}_{CO_2} / \dot{V}_A) \quad (49.5)$$

It will rise if CO_2 production increases and is not balanced by an appropriate rise in alveolar ventilation, or if alveolar ventilation decreases at a given CO_2 production. Therefore, the P_{aCO_2} is an index of the adequacy of alveolar ventilation in relation to carbon dioxide production.

Alveolar ventilation is that portion of the total minute ventilation (\dot{V}_E) that participates effectively in gas exchange. The remainder of minute ventilation reaches only anatomic or physiologic dead space; it does not participate in gas exchange and is called *dead space ventilation* (\dot{V}_D). Alveolar ventilation, then, is total minute ventilation minus dead space ventilation.

$$\dot{V}_A = \dot{V}_E - \dot{V}_D \quad (49.6)$$

Alveolar ventilation may fall due to a decrease in minute ventilation with a normal dead space, or due to an increase in dead space ventilation without a compensatory increase in minute ventilation.

Oxygen is essential for aerobic metabolism. The transfer of oxygen from alveolar air to pulmonary capillary blood is affected by the partial pressure of oxygen in the alveoli, its diffusion across the alveolar-capillary membrane, and the matching of alveolar ventilation to capillary perfusion. There are five possible causes of a reduction in P_{aO_2} : low inspired oxygen tension, alveolar hypoventilation, diffusion impairment, ventilation-perfusion mismatching, and right-to-left shunt. In addition, a low mixed venous oxygen tension will magnify the reduction in P_{aO_2} due to ventilation-perfusion mismatching and shunt.

The partial pressure of oxygen in the alveoli (P_{AO_2}) may be determined from the ideal alveolar gas equation,

$$P_{AO_2} = (P_B - PH_2O)F_{IO_2} - (P_{aCO_2}/R) \quad (49.7)$$

where P_B is barometric pressure, PH_2O the partial pressure of water vapor (47 mm Hg), F_{IO_2} the fractional concentration of inspired oxygen, and R the respiratory exchange ratio (usually 0.80). The alveolar-arterial oxygen tension gradient, $P(A-a)O_2$, is the difference between calculated P_{AO_2} and measured P_{aO_2} . The normal gradient increases with age, but is usually in the range of 5 to 20 mm Hg. If either alveolar hypoventilation or a low inspired oxygen tension is the cause of a decreased P_{aO_2} , this gradient remains normal. In contrast, an abnormality in either diffusion or ventilation-perfusion matching will increase $P(A-a)O_2$. Diffusion, however, is rarely the cause of a low P_{aO_2} at rest.

Arterial oxygen content (CaO_2) is the sum of hemoglobin-bound oxygen and dissolved oxygen

$$CaO_2 = 1.34 (Hb)(SaO_2) + (0.003)(PaO_2) \quad (49.8)$$

where Hb is the hemoglobin concentration and SaO_2 the arterial O_2 saturation. The contribution of dissolved oxygen is very small, and the major impact of P_{aO_2} on oxygen content is through its effect on hemoglobin saturation (Figure 49.1). Above a P_{aO_2} of 60 mm Hg, the dissociation curve is relatively flat and SaO_2 increases very little even with a large increment in P_{aO_2} . In contrast, below P_{aO_2} 60 mm Hg, the curve is steeper and SaO_2 decreases significantly with any decrement in P_{aO_2} . Also, as illustrated in Figure 49.1, the position of the oxyhemoglobin dissociation curve may be shifted by factors that alter the configuration of the hemoglobin molecule and change its affinity for binding oxygen.

Oxygen delivery to the tissues is the product of cardiac output and arterial oxygen content. Oxygen delivery can be compromised by a reduction in any component (cardiac output, hemoglobin concentration, or SaO_2). However, a decrease in one component may be offset by an increase in another to maintain oxygen delivery.

Clinical Significance

An ABG contains data relevant to three areas: acid-base status, ventilation, and arterial oxygenation. Clinical esti-

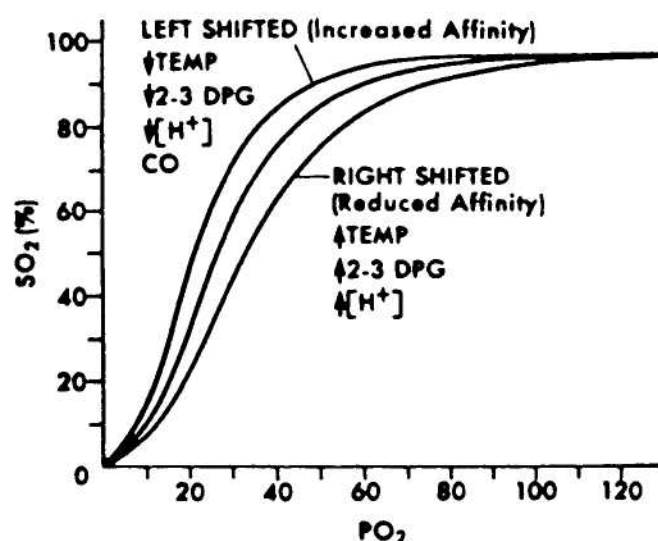


Figure 49.1
The oxyhemoglobin dissociation curve and variables that affect oxygen-hemoglobin affinity. 2-3 DPG = 2,3-diphosphoglycerate; CO = carbon monoxide. From Kryger MH, ed. Pathophysiology of respiration. New York: Wiley, 1981. Reprinted with permission.

mates of the presence or severity of abnormalities in these areas are often deceptive. Consequently, an ABG is useful when disturbances are apparent or suspected in any of the three parameters. A systematic approach to interpretation, in conjunction with appropriate clinical correlation, will help delineate problems in each of these areas and will guide the institution and adjustment of supportive therapy when necessary.

First, consider the acid–base status. The simple acid–base disorders are presented in Table 49.2. The differential diagnosis for each category is relatively limited and may be found in most medicine texts. Diagnosis is often aided by using other laboratory parameters, such as serum electrolytes, along with the ABG and clinical data. Treatment should be directed toward the underlying cause and will depend on the nature and severity of the disturbance. Prompt intervention is generally necessary at the extremes of acidemia ($\text{pH} < 7.20$) and alkalemia ($\text{pH} > 7.60$) because adverse effects on the cardiovascular and central nervous systems are common when pH exceeds these limits.

Next, the ventilatory status should be evaluated. While this is an extension of the acid–base analysis, it focuses attention on ventilatory function. Recall that the PaCO_2 is an index of the adequacy of alveolar ventilation in relation to carbon dioxide production [Eq. (49.5)]. Normally a primary rise in PaCO_2 will trigger an increase in ventilation and restore the PaCO_2 if the respiratory pump is intact. Hence, when hypercapnia and respiratory acidosis are present, some degree of ventilatory failure has occurred. Common causes include central nervous system depression or disease, neuromuscular disorders, thoracic cage deformities, and obstructive lung disease. In addition, respiratory muscle fatigue due to increased work of breathing from any cause may culminate in ventilatory failure. If the respiratory acidemia is severe or progressive, mechanical support of ventilation may be necessary while other measures are directed at the underlying process.

Finally, arterial oxygenation should be assessed. A PaO_2 below the predicted lower limit of normal [Eq. (49.2)] or a widened P(A-a)O_2 indicates an abnormality in gas exchange that should be recognized, but may not always significantly impair arterial oxygenation. A PaO_2 of 60 mm Hg provides approximately 90% hemoglobin saturation if acid–base status and temperature are normal (Figure 49.1). However, below PaO_2 60 mm Hg significant desaturation occurs as

the PaO_2 falls, and arterial oxygen content [Eq. (49.8)] decreases proportionately. When oxygen delivery is compromised by a low arterial oxygen content (desaturation, anemia) or by an inadequate cardiac output, critical tissue hypoxia may occur. The most sensitive sites are the central nervous system and the heart, but oxygen deprivation is potentially harmful to all aerobic, metabolically active tissues. In most clinical circumstances a reasonable goal of therapy is to maintain the PaO_2 in the 60 to 80 mm Hg range. In some cases, slightly lower levels may be acceptable; however, there is generally little to be gained by increasing the PaO_2 substantially above this range. When needed, supplemental oxygen should be administered with these guidelines in mind. In addition, attention should be given to hemoglobin concentration and cardiac output to optimize oxygen delivery.

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